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A conceptual framework for incorporating competitiveness into network-level transit quality metrics

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ABSTRACT

In today's mobility context, people have more mode choices than in the past, and many of those new choices are auto-based. This has led to a resurgence of transit agencies rethinking their networks and how well they connect people to opportunities. This paper proposes a new theoretical framework, Competitive Access, for transportation researchers and practitioners to use in describing and measuring regional transit access. The Competitive Access framework incorporates the concept of competitiveness between auto-based modes and transit, and is flexible enough to capture the varying contexts in which accessibility can change between and within regions. Using this framework, we propose two measures that describe the trip coverage and regional access provided by a transit network. These measures better reflect the realities experienced by riders in comparison to traditional access measures. Additionally, this paper includes a guide for practitioners to implement the framework and its associated measures in a network redesign context.

1. Introduction

The Massachusetts Bay Transportation Authority (MBTA), like many of its peer agencies, has faced a decline in bus ridership in recent years. Moreover, current MBTA riders have expressed that the transit system does not fully give them access to places they need to go. At the same time, with the rise of transportation network companies (TNC) and cheaper auto loans, it has become easier to access auto-based modes of transportation. Transit has to exist in an increasingly competitive transportation market where transit riders have access to many auto-based modes, including personal automobiles, TNCs, ridesharing, and taxis, that all compete with transit as well as each other (Ravle et al., 2016).

Yet, measures of transit quality that do not take into account the relative quality of transit versus auto-based modes make the assumption that transit riders are "captive" to transit, when in fact many transit riders also use auto-based modes and must therefore be making decisions between transit and auto-based modes for at least some of their trips (National Academies of Sciences, Engineering, and Medicine, 2018, TCRP Report 195; Gehrke et al., 2018).

The primary goal of transportation is to get people where they need to go (as visible in the paradigm shift from mobility-focused transportation planning to accessibility; Koenig, 1980; Cervero, 1996; Levine and Garb, 2002; Ganning, 2014; Boisjoly and El-

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Geneidy, 2017). Thus, any measure meant to assess the quality of a transit network should capture the amount of **access** that network is providing to the region. That is, is transit creating the connections necessary for people to reach destinations that matter to them? Additionally, any network quality measure needs to take into account **competitiveness**, because beyond just creating connections, we want to make sure that we are serving those connections well, with high-quality transit, such that transit is a reasonable choice for that connection.

In general, transit agencies, and oftentimes researchers, tend to measure the success of a network by quantifying the time it takes a user to reach a specific destination (Lei et al., 2012; Gulab and Martens, 2014; Benenson et al., 2016; Boisjoly and El-Geneidy, 2016). Some agencies may further specify this measure by selecting a specific amount of time to access a location (e.g. jobs that can be reached through the transit system in 45 min). This way of gauging success, while helpful as a measure of geographic coverage, fails to take into account the fact that prospective transit users may substitute a transit trip with a faster mode even if it is within the specified time, as well as the fact that transit users consider factors other than travel time in deciding if a trip is competitive or not (e.g. Frank et al., 2008; Thistle and Zimmer, 2019).

This concept of competitive transit relative to auto-based modes of travel is extensively researched in individual trip-level decision making (Saelens et al., 2003; Smith et al., 2005; El-Geneidy et al., 2009; Ellison and Greaves, 2011; Cervero, 2013), and is generally considered for route-level analysis by service planners (Smith et al., 2005). However, network-level measures in use by transportation agencies haven't generally scaled up from this trip-level concept (Boisjoly and El-Geneidy, 2016). A recent exception in this trend is the ongoing Los Angeles bus network redesign, which has been based on the competitiveness of transit versus auto-based modes (Arellano Associates, 2019), and some research work is moving in this direction (e.g. Cai et al., 2017). The proposed framework takes the trip-level concept and aggregates it to the network level, where the transit network is evaluated for all of the trips made in the region.

With access and competitiveness as the two guiding concepts at its foundation, the Competitive Access framework provides researchers and practitioners with a simple, but comprehensive, new method for measuring network quality. This is done through two primary measures that gauge the level of competitive transit access to local and regional destinations as well as the number of trips that have a competitive transit option.

This paper is organized as follows: the next section (Proposed Framework - Competitive Access) outlines the conceptual framework in more detail. The following section (Implementation Guides) provides implementation guides for the decisions that need to be made in order to calculate the measures for a region using the example of the Massachusetts Bay Transportation Authority's Bus Network Redesign. The last section (Discussion) recommends next steps and reviews limitations of this approach.

2. Proposed framework - competitive access

2.1. Concept

The Competitive Access framework outlines the critical elements of any metric that measureswhether the transit network provides high-quality service.

First, any network quality measure needs to take into account travel demand. The network should be described by its ability to create connections between where people are and where people want to go (Koenig, 1980; Cervero, 1996; Levine and Garb, 2002; Ganning, 2014; Boisjoly and El-Geneidy, 2017). The universe of travel demand in a region includes the trips that people are currently making, but should also incorporate some element of latent travel demand (Handy and Niemeier, 1997). Path dependency and the network design may prevent some people from accessing destinations they would otherwise travel to, and particularly for equity reasons, these "potential trips" should be incorporated into a competitive access measure.

Second, transit's competitiveness versus auto-based modes should be incorporated into any network level measure. In today's mobility context, people have more mode choices than in the past, and many of those new choices are auto-based. If we truly want to design a network that encourages mode shift for both environmental and economic reasons, we should evaluate our networks on their competitiveness, since mode shift from auto-based travel is expected to occur more frequently when transit is a viable option for trip-making (Koenig, 1980; Ellison and Greaves, 2011). Service planners often design routes with competitiveness in mind (Smith et al., 2005), but this approach has not generally been incorporated into network level measures (with the notable exception of one recent attempt, Cai et al., 2017). Competitiveness, in this framework, is what we are using to define high-quality transit. In other words, we should measure whether or not a transit network is providing high-quality service by measuring whether transit has the features that would make a person potentially choose riding over an auto-based mode.

Third, because we are using the idea of individual decision-making to set the standard for high-quality transit, any network quality measure should be flexible enough to allow for multiple definitions of competitiveness. The considerations of an individual when choosing a mode can vary significantly (Scheiner and Holz-Rau, 2007; Aarts et al, 1997). Measuring network quality with the trip as a unit of analysis allows for different "competitiveness formulas" (i.e., the combination of different factors an individual considers when choosing a mode) to exist.

Different characteristics of trips and people can affect how an individual perceives the quality of transit. For example, travel time and frequency can be important factors when choosing transit as a commute mode. However, for a grocery shopping trip, door-to-door service may become increasingly important. Similarly, a person with limited mobility has a very different set of needs from an able-bodied person (Hess, 2012) and those differences may result in a different set of considerations for travel.

Additionally, when competitiveness between transit and auto-based modes is used as a measure of transit quality, often travel time used as the only point of comparison (Cai et al., 2017, Arellano Associates, 2019). However, multiple factors can and do play a part in mode choice; number of transfers, frequency, and reliability of service come up often in individual choice research. A transit quality measure should be able to capture those factors for the region.

Not only are there multiple factors of competitiveness, but there may be varying thresholds at which transit becomes competitive. It should not be assumed that a one-to-one comparison is the default way in which people make transportation choices. Most research shows this is not the case (for example, National Academies of Sciences, Engineering, and Medicine, 2013 indicates that transit can have a travel time ratio of 1.5 in comparison to driving; the LA network redesign used a ratio of 2, Arellano Associates, 2019). These thresholds can be expected to vary regionally, by trip purpose, and/or by demographic characteristics.

Fourth, because the Competitive Access framework necessitates the consideration of travel demand and modal competitiveness, the unit of analysis for any network quality measure should be a trip. Trip-level analysis allows for different “competitiveness formulas” to exist within one singular measure because each trip can be measured against its driving equivalent. Trips, as a unit of analysis, can then be aggregated in a variety of ways to understand how well the network meets demand overall or for particular groups of individuals or types of trips.

Fifth, equity is a critical component of public transit’s role in a region and should be incorporated into any and all network quality measures. Oftentimes in transit network evaluations, equity is not measured at all, or is included as a stand-alone measure developed specifically to address equity concerns, creating tensions that pit “operational efficiency” (i.e. high ridership at low operational cost) against “equity mandates” (e.g. coverage of environmental justice neighborhoods) (Wei et al., 2017). We propose that equity should be incorporated into any network quality measure so it is built into the measurement and understanding of what is “good transit”.

While the framework uses competitiveness against auto-based modes to set the standard for high-quality service, it does not limit this standard to evaluation of the trip-making by people for whom driving is an option. In fact, this method of defining good transit sets a more stringent standard for the quality of service that is provided to zero-vehicle and low-income households than typical access measures (Karner and Niemeier, 2013).

Additionally, because most network level quality measures are geography-based, home-based trips are commonly the only ones evaluated for equitable access. However, a large amount of travel is non-home based, and measures should attempt to capture actual trip-making by vulnerable populations, regardless of whether that travel is occurring in an EJ community.

Sixth, while network quality measures should incorporate all of the above considerations, they should also be simple to explain and implementable. In the academic literature, many researchers have incorporated the above principles into access measures, but oftentimes through onerous statistical modeling and technological workarounds that make implementation nearly impossible by an agency. The best evidence of this is that policy-makers consistently use simple to calculate, but indirect cumulative opportunity measures to evaluate the quality of a transit network (Boisjoly and El-Geneidy, 2016; Boisjoly and El-Geneidy, 2017). Measurement complexity should complement the expertise within a transit agency. Complexity surrounding network design decisions and provision of service, elements that transit agencies are equipped to understand and evaluate, is preferable to complexity of statistical methods and modeling approaches. Technological advancements in data collection and routing have made it easier to focus more on comprehensive measurement concepts that take into account nuances of transportation systems.

2.2. Implications of the competitive access approach

Using the Competitive Access framework to measure network quality has implications for which features of transit network designs tend to be rewarded by these measures.

First, transit networks, and their common measures of success, are often centered on commute patterns. This leads to networks that contain more frequency during the peaks and routes primarily focused on bringing people into the Central Business District or other major employment hubs. By considering all trip purposes, and ultimately declaring that a transit network is responsible for serving all trip purposes equally, measures built from this framework will deemphasize commuting (which only makes up 16% of trips, Polzin and Pisarski, 2013) and reward designs that include features like all-day frequency. Although this is a distinct theoretical shift, in practice, because employment centers also generate other trip purposes, the evaluation of the transit network’s quality will likely not change drastically from more commute-oriented measures.

Second, because this framework necessitates a trip-based measure, it will reward trip coverage (providing service in dense areas with a lot of concentrated demand) and deemphasize geographic coverage. This, in combination with the stringent service standards set by competitiveness, means that lifeline service will not be rewarded by a competitive access measure. This is particularly important to note, because many transit agencies have coverage goals as well, and these goals will need to be assessed using a complementary measure outside of the Competitive Access framework.

Additionally, this approach rewards transit when it is competitive against auto-based modes, even when both modes are perceived as underperforming by riders. For example, in highly congested areas, this can mean counting transit as competitive even if it takes 50 min to cover 10 miles, as long as the auto-based alternatives take even longer. Due to the fact that this framework measures transit quality by comparing it to auto-based modes, improvement (or decline) in the measure can either be induced by changing the quality of transit or by changing the level of congestion. Increased congestion, which worsens the auto-based alternatives, would improve the Competitive Access measure without any actual transit quality improvements. Similarly, improvements in congestion would decrease the Competitive Access measure without any actual transit quality deterioration (as with the decline in congestion and gas prices during the ongoing COVID-19 pandemic). We believe this to be reflective of how people actually make mode choice decisions, but it is a deviation from traditional measures of transit access.

2.3. Proposed measures

Using the Competitive Access framework, we propose two different measures that can be used by researchers and practitioners to assess the quality of a transit network. These proposed measures are simple, but incorporate all of the framework considerations listed above (see: Concept). This section describes the measures at a high level; the following section describes the "under the hood" decisions that need to be made in order to be able to calculate these high-level measures for different goals (as long as mode shift and/or regional access to opportunities were important concepts to measure). The following Implementation Guides section contains more in-depth coverage of how we operationalize these measures with the goal of evaluating different transit alternatives in a bus network redesign.

The first measure focuses on creating a system where transit is a competitive option with driving in order to encourage mode shift from auto-based modes and to prevent mode shift from transit to auto-based modes. Mode shift produces a variety of benefits to a region: reducing emissions, reducing congestion, promoting public health, and maintaining revenue to fund a high-quality transit system for those who need it. The more individual trips we can convert from auto-based modes to transit, the higher the benefits. We can only expect to shift current auto-based trips onto transit if we provide a reasonable transit option *for that trip*. Similarly, we can only expect to keep transit riders long-term if the transit we provide is competitive for them now; otherwise as soon as other options become available to the current riders, we can expect them to switch to more viable alternatives. Further, equity is incorporated into the measure; there will be separate calculations for trips made in the region as a whole and also for trips specifically made by low-income populations and people of color.

Trip Coverage measure:
the proportion of the region's trips
(by low-income people and people of color)
that have a competitive transit option.

The second measure focuses on competitive access to regional and local destinations relevant to the residents of the region. This measure does not assume that all desired trip-making already happens; it evaluates whether competitive transit access exists should residents choose to go to regional and local centers, whether or not they make those trips now. Since this is a residential measure, whether competitive access is equitably distributed can be evaluated by calculating the measure separately for EJ community residents and comparing to the overall competitive access measure.

Regional Access measure:
the proportion of residents
(in environmental justice communities)
that can reach their local and regional destinations
with a competitive transit option.

Both measures are mathematically very simple. Each measure starts with a "universe of travel." For the trip coverage measure, the universe is comprised of all trips (O-Ds) in the region, and for the regional access measure, it is a set of O-Ds that represent travel from each residential geography to a set of important destinations. Each trip (or O-D pair) is then evaluated individually to compare driving and transit-based on the definition of competitiveness being used. Finally, those individual evaluations are then aggregated in order to measure the proportion of trips (or destinations) for which transit is a competitive option.

Because the measures are simple aggregations of trip level analysis, both measures could be subset to explore the network's performance in particular contexts. The most obvious example of this is the equity component of the measures. Instead of using the universe of travel as the measure denominator, the denominator could become all trips taken by low-income people and people of color (for the trip coverage measure) or all potential home-based trips from environmental justice communities (for the regional access measure). Additionally, particular types of travel can be evaluated as separate universes as well (e.g. travel during a certain time of day, or travel during a ban on non-essential travel due to a pandemic, or travel originating from a particular municipality within the region). Likewise, particular trip purposes can be measured individually.

Additionally, the same measure can be calculated multiple times using different competitiveness formulas to evaluate trip-making. This could be done, for example, when evaluating how well people with disabilities are being served by a transit network. While low-income populations and people of color are often geographically concentrated, people with disabilities are typically dispersed throughout a region. The entire trip universe can be evaluated against a competitiveness formula designed specifically for people with disabilities. Ultimately, an agency or a research team will end up with a variety of competitive access scores for different contexts.

Additionally, this framework stops short of recommending targets; depending on the decisions each region will have to make about what "counts" as competitive transit under their system, what is a reasonable target will vary. A region may determine that 15% of its trips have a competitive transit option, and decide to aim for 20%. A different region may have a different scoring approach, where 50% of its trips have a competitive transit option for commute trips, but only 20% of the trips have a competitive transit option for people with disabilities. They may decide to focus on addressing the disparity, and therefore set a different target. Because the competitive access framework output is so simple, the target-setting can be flexible to allow for different areas of focus or improvement in each region.

While the high-level measures are simple in order to create meaningful, actionable, and easy to communicate results at the network level, there are many underlying decisions that need to be made specifically to define what makes a transit trip competitive compared to an auto-based trip. The following section describes the major concepts that need to be considered in making that decision.

2.4. Defining competitiveness

One of the major conceptual decisions of this framework is what elements of service should be counted in a competitiveness definition. On the transit side of the equation, there are two main categories of service measures: elements of the scheduled network and elements of provided service quality. Elements of the scheduled network include aspects like distance to access service, scheduled frequency, number of transfers, and scheduled trip travel times. Elements of provided service quality include aspects like actual frequency, travel times, reliability and variability of travel times, as well as conditions on board (e.g. comfort, crowding).

Scheduled network measures are best for evaluating the conceptual design of the transit network independent of how well it is provided; it is best for answering questions like, "how competitive is the network that we have designed if it were operated as scheduled?" and "are there inequities in how we are designing and scheduling our network?" These measures are also good for evaluating possible networks against each other when conducting a major network revision or redesign and where service quality measures are nonexistent because the networks are theoretical.

Service quality measures are important to incorporate when measuring the quality of service as it is experienced by riders. It is entirely possible to *schedule* a very equitable network but fail to *provide* an equitable network (for example, if similar levels of service are scheduled but reliability and crowding are worse in dense urban neighborhoods that also happen to be low-income communities or communities of color). Service quality measures are best at answering questions like, "how competitive is the network we actually provide to riders?" and "are there inequities in the quality of provided service within the region?"

Ideally, it should be possible to evaluate both the scheduled transit network and the provided transit network for competitiveness against auto-based modes. If the scheduled network does not create competitive transit options for many trips, the transit network may need to be re-evaluated. However, if there are discrepancies in competitiveness between the scheduled and provided service, that would likely point to possible intervention locations for transit signal priority, dispatching improvements, and other changes to close the gap between scheduled and provided service in impacted areas.

On the auto side, there are comparatively fewer elements of interest, with travel time being the most salient. Additional measures may include cost (direct costs for TNCs or indirect costs for car ownership), parking constraints (either as additional time or cost), and variability in travel time.

2.5. Calculating competitiveness

In order to calculate the measures in this framework for a region, the following data is assumed to exist:

- A dataset of all travel in the region in O-D pairs, mode and trip purpose agnostic (e.g. cell phone data; household travel surveys), scaled up to represent all travel in the region
- Access to a routing solution for transit and driving (e.g. Google Directions API, OpenTripPlanner)
- Demographic data for equity calculations

The backbone of this analysis relies on having an origin-destination (O-D) dataset for the study region. This can come from location-based services data (gathered through smartphone applications), cell phone triangulation, or household travel surveys – whichever method works as long as the dataset is representative of the whole region. This data is used to identify all the trips that are occurring within a region, as well as the volume of those trips. A key consideration when it comes to the O-D dataset is the geographic aggregation it should be in; in its least aggregated form (device-level), the data is both unwieldy due to the large quantity of trips, and has several privacy concerns that need to be addressed, making it difficult to either obtain it in this shape in the first place or use it for analysis. Instead, an agency needs to consider a geographic aggregation level that meets the needs of the network it is analyzing.

The main research question and the associated elements of transit and auto qualities also need to be identified early on in the process because there are important data implications that stem from this decision. To evaluate the quality of scheduled service, a transit agency needs to use or create a dataset of its schedule (e.g. GTFS, outputs from scheduling software) that can be used to create transit itineraries for trips through a routing solution. Additionally, analogous datasets also need to be created for car trips to reasonably capture the quality of the auto-based modes (e.g. travel times and reliability of the car trips could be created from historical congestion data). To evaluate the quality of service provided, an agency would need to have information of how this service looked like for that time period (e.g. dropped trips, experienced wait times, reliability as experienced by riders).

This is further complicated when evaluating different transit network alternatives. As these alternatives are hypothetical, it is not possible to actually evaluate the quality of service provided; instead, the evaluation focuses on how the quality of scheduled services compares among the alternatives. This means that an agency would have to produce accurate alternative schedule data that is comparable to the current network, generate routing information, and apply the same scheduled service performance measures to compare against each other.

The Implementation Guides below discuss the decisions we made for purposes of evaluating different transit network alternatives for the MBTA's Bus Network Redesign as an illustrative guide, with some commentary on expanding the methodology to transit quality.

3. Implementation guides for network redesigns

At MassDOT/MBTA, we focused our measures to primarily capture the effects of the network design and the potential improvements that could be provided by alternative networks (in part to guide our current Bus Network Redesign initiative). The main goals for the Bus Network Redesign are to reduce transportation emissions by supporting the ability to live car-free and attracting ridership from cars; to deliver a high capacity transportation network that supports the regional economy and local living; and to provide competitive service and increase access for vulnerable populations (low-income people, people of color, and people with disabilities).

In order to develop a measurement system that addresses each of these goals in the context of multiple transit network alternatives, we are including factors that are directly affected by a network's design, even though these do not encompass all of the factors that go into individual decision-making around mode choice and perceived competitiveness. The factors we are using are:

- Total travel time (as a direct measure of comparison against auto-based modes),
- Frequency (as a measure of convenience/availability of walk-up service),
- Number of transfers (as a measure of additional inconvenience over auto-based modes), and
- First/last mile distance (as a measure of additional inconvenience, especially for certain trips and riders).

Network quality factors (e.g. reliability, cost, safety, and communications) are important to individuals' perceptions of transit, and certainly important to people's willingness to actually use transit, but are not controlled by the network design, and thus will not vary between different design alternatives.

3.1. The role of data

3.1.1. Travel demand dataset

For the Bus Network Redesign at MassDOT/MBTA, we are using a Location-Based Services (LBS) dataset that allows us to understand all travel in and around the MBTA service area. The dataset contains 42.5 million trips in the Boston Metropolitan Statistical Area (MSA) in 2018.

There are limitations to the representativeness of the data; specifically, because it is limited to people who have smartphones, we have to assume that people who do not have smartphones travel in the same patterns as those who do. Because a high proportion of most demographic groups have smartphones, this is an unproblematic assumption. However, seniors are particularly underrepresented in the universe of smartphone ownership, with only 53% of U.S. adults over 65 owning a smartphone, compared to 81% of all U.S. adults (Pew Research Center, 2019). Therefore, seniors are also underrepresented in the LBS dataset. Because seniors frequently have different transportation needs as well, this is a problematic gap in our knowledge of regional travel. Therefore, we will be supplementing the LBS information with other local data to ensure the movement data better reflects how people travel throughout the region. In addition, our metrics take into account that not all trips that people want to make will be in this dataset (e.g. particularly for transit-dependent communities, trips taken may be limited by transit availability).

3.1.2. Demographic data

The LBS dataset identifies which block group is a device's home. Based on 2013–2017 ACS data, we identified median income and percent residents of color for the MBTA service area. We flagged block-groups as low-income if their median income was below the MBTA service area median, and as communities of color if the percent of residents of color was higher than the service area median. Each device was given the relevant equity tag if it lived in either a low-income block group or a community of color (many devices were tagged with both equity tags). The equity tags follow the devices as they travel, so even if a low-income tagged device, for example, is traveling between two high-income areas, the trip would still show as a trip taken by a low-income tagged device.

3.1.3. Final structure of travel demand data

The LBS trip data was initially aggregated to commonly-used census geographies (census block groups) and time periods used in transit service delivery to preserve privacy and reduce the size of the dataset. This level of aggregation is important in assigning demographic information and creating multiple travel datasets for equity evaluations.

However, census block groups are sized to be comparable in population counts, but transit service is provided to a geographic area rather than to a population. Some census block groups are so geographically small that if we were to consider them as the base unit of analysis for bus service, we would end up artificially rewarding provision of service for some extremely short trips, especially in the downtown core. A critical decision involves setting the coverage of transit service; that is, what area can be considered as being "served" by a transit stop.

For purposes of evaluating differences between different network alternatives, we created groups of block groups, which we call Bus Analysis Zones (BAZ), with the goals of creating roughly similarly-sized geographic areas up to approximately ½ square mile, with the assumption that if a network design serves that BAZ, it can be considered as serving all the trips originating in roughly that ½ square mile. Where possible, we also used local knowledge to combine block groups that comprise meaningful neighborhoods and made sure to not cross municipal boundaries so that we could continue to report results at the municipal level.

The working travel dataset contains device level origin-destination (OD) demand assigned to BAZs, differentiated by weekday and weekend; time of day; and general trip purpose (home-based regular travel; home-based other; and non-home based). The trips are scaled based on the device's inferred home location to the U.S. census tract population to represent the travel in the tract.

This assignment process creates the final table structure for the high-level measures. It is important to note that the aggregation decisions made in this dataset greatly impact the form of the other datasets, as it serves as the unit of analysis that is used throughout the whole framework. In our case, since we aggregated origins-destinations to BAZs, time periods, and day types, the rest of the analysis, including both transit and car pathing, can only be done at that level. This means that each BAZ-pair by time period and day type will be routed and analyzed for competitiveness. This can reduce some of the nuance that less disaggregate data can display (such as more accurate travel times at the device level). An agency interested in doing this analysis will have to decide what is the most feasible while still accurate aggregation level.

In the following sections, we discuss how this table will be populated with routing/pathing data, transit and auto trip quality assessments, and the final competitiveness evaluation. When we discuss a "row" in this table, we mean specifically the origin BAZ-destination BAZ-time period combination that is our base evaluation and reporting unit in this table. Additionally, there will be at least three final tables: one for general travel, one for devices tagged with "living" in a low-income community, and one for devices tagged with "living" in a community of color. Additional tables with other travel characteristics (e.g. essential-only travel) can be constructed as needed with the same geographical and temporal assignments.

3.1.4. Options for obtaining or generating travel itinerary datasets

The routing solution will likely depend on data aggregation decisions, on budget, and technical/analytical capacity; for example, OpenTripPlanner, an open-source multimodal trip planning software, is free but relatively intensive to set up and use. An agency would need to be able to set up an instance of the software, upload a compatible schedule (usually GTFS), and set up appropriate "costs" for the routing software to generate plausible trips. Additionally, an agency would also need to ensure that the tool is able to produce accurate car trips as well, and reflect travel times that take congestion into account. One thing to note is that, while for transit trips it is necessary to obtain the actual itinerary of the trip (in order to take into account transfers, etc.), for evaluating different transit network alternatives, car trips only need travel times and not exact pathing.

Paid options such as the Google Directions API are easier to use but charge a fee per API call. This can add up to a significant sum when working with disaggregate origin-destination data. Moreover, the Google Directions API will not allow changes to the underlying GTFS file used for transit routing, meaning it is not possible to use it to evaluate alternative transit networks. Additionally, the Directions API, like many other proprietary software, does not provide access to the algorithms or data it uses to determine trip feasibility and trip times, which means an agency has to simply believe the output of the software. There are other routing tools that an agency may use that fall into the paid category that are more customizable, but may be cost-prohibitive.

For the MBTA Network Redesign, we originally conducted the routing using the Google Directions API. This method produced suboptimal travel times, as they appeared to underestimate the average time traveled between destinations. We are now considering alternative options using OpenTripPlanner for transit and StreetLight for car travel times.

3.1.5. Routing aggregation for the final table structure

A major decision regarding routing is whether to route at a disaggregate level and then to aggregate to one value per row of the final table structure, or to route at the aggregate level. This decision is likely to have cost implications - the more trips are routed, the more it may cost to create the dataset. At MassDOT/MBTA, we're considering aggregating to time periods (early morning, AM peak, mid-day, etc) and BAZ level; we're evaluating this level of aggregation against the completely disaggregate trip level routing in order to see the impact on the final measure and the directional influence on accuracy. Aggregation to BAZ-level geography (i.e. routing centroid-to-centroid and applying that routing for all trips in those BAZs) will eliminate variation in routing characteristics such as walk distance to transit and total travel time. If the travel dataset makes up a relatively low percentage of total travel, regardless of how representative it is, the connection between this variation and the specific ODs is likely to be arbitrary.

Aggregation to a time-period could be done in a variety of ways. In a semi-disaggregate approach, one could route an OD at a variety of different trip times (e.g. every half hour) and then assume that travel is evenly distributed across a time period. This option may be the least consistent with reality if travel is particularly bunched within a small piece of the time period (e.g. a peak within a peak period), and transit is substantially more or less competitive during this time. However, if the assumption of random arrivals is reasonable, this option would allow metrics to reflect the variation in reality if some but not all of the transit itineraries connecting an OD are competitive. Alternatively, one could route an OD at a variety of different trip times and then assume that people will leave at the time that affords them the most competitive option. This option artificially rewards the Network Design in contexts where individuals have very little control over the exact timing of their trip, but more accurately reflects the choices that people would make if they have the flexibility to plan their exact departure time around the most competitive transit option.

We will compare the more disaggregate measure to the aggregate measure to assess the magnitude of the impact and under which contexts the measures are most varied. If, for example, the time aggregation only has an impact on commute trips, this may be an unreasonable abstraction, since individuals are fixed in their commute times, but if the time aggregation mainly has an impact on non-commute trips, it is likely to be rewarding the system in a way that is consistent with travel behavior. Each point of aggregation found to be reasonable will reduce the number of calls to the routing API, and will need to be scaled back up to the number of trips represented by each call.

3.2. Trip coverage measure implementation guide

Measure: the proportion of the region's trips (by low-income people and people of color) that have a competitive transit option under each transit network alternative.

This measure is focused on the environmental goal of reducing emissions by supporting the ability to live car-free and attracting ridership from cars. This goal is evaluated using current travel patterns in the region; it presupposes the use of a dataset of all travel in the region, including all mode and trip purposes. The following decisions need to be made in order to calculate the measure:

3.2.1. What counts as the universe of trips (the denominator in the proportion)?

The largest impact of this decision is likely to come from the threshold of a minimum distance that makes a trip “count” in the universe of trips for which good transit needs to be provided. For example, Cai et al., 2017, sets the minimum threshold at double the expected walk distance to access service (they use 1000 m as the minimum distance for trips that “count” in the denominator). This is likely to vary due to regional factors like overall density, sidewalk coverage, and other factors that make walking a more or less reasonable decision for short trips. Where short trips are likely to be made by active modes, it’s less important to provide high-quality transit service for them from an environmental perspective (there are no emissions savings from competing with active modes). However, in a region where even short trips are likely to be made by auto-based modes, it may make more sense to consider shorter trips in the denominator of this calculation. At the MBTA, we are considering what the exact minimum threshold should be; it will likely vary for different contexts, but we expect that it will be around approximately one mile, since that is the average reported trip length for trips using active modes (FHWA NHTS Brief, 2020).

In addition to setting the minimum trip distance, which will be the most defining element (it will remove the most trips from the denominator since a high proportion of travel is short trips), the main other decision that needs to be made is the boundary of the region. At MassDOT/MBTA, we have set the boundary at the municipalities that are served by the bus network (excluding some of the municipalities on the edges of the system that are only served by regional rail service); a decision to include all served municipalities would have expanded our denominator to include all travel in those regions. The reasoning for this decision included consideration of other transit authorities that operate bus services in those municipalities; we are not currently evaluating the competitive transit access provided by non-MBTA transit authorities, although that is one reasonable expansion of the framework.

These were the only limiting factors we have implemented at this point, but one could also reasonably consider removing from the universe of trips travel that would never be served by the transit agency. For example, if a region would not realistically implement late-night transit service, it may make sense to remove late-night travel from the denominator in general.

3.2.2. Which competitiveness factors are on the table for evaluation?

This decision will determine what parameters need to be captured in the routing or merged in from other datasets. At MassDOT/MBTA, because we are focused on elements of network design as described above, to evaluate the trip’s transit quality, we need to capture the walk distance, number of transfers, and total travel time. Additional information about specific transit services for the trip are necessary for competitiveness formulas that incorporate service-specific factors (e.g. frequency), which vary by route. To evaluate quality of the auto-based modes, we are only capturing total travel time and none of the pathing information, since that will not vary between transit network designs.

3.2.3. How will you aggregate data from the level at which it was routed to the level determined for the travel demand dataset?

The trip coverage metric requires a single answer as to whether or not each row of data in the travel demand dataset has a competitive transit option. At MassDOT/MBTA, we are aggregating our travel demand data to each Origin BAZ-Destination BAZ-time period combination, so we need to determine whether or not each unique combination has a competitive transit option.

If the routing was performed at the same level of aggregation as desired in the final travel demand dataset (the advantages and limitations of which were discussed in Section 3.1.5), no aggregation is necessary – each row of data will be separately tested for competitiveness. However, if the routing was performed on data more disaggregate than the final travel demand dataset (e.g. if every trip was routed), it must eventually be aggregated back to the level desired for the final table structure. Aggregation can be done at one of two times: either before applying a competitiveness formula to the row in the final dataset, or after applying a competitiveness formula to each unique routing that was produced.

Aggregating before the application of a competitiveness formula constitutes using the disaggregate routing to calculate a “composite trip” for each row in the final dataset. For example, one could take either the mean or median of all of the individual initial walk distances to transit and assign this average to be the initial walk distance associated with the row in the final dataset. The resuling composite trip would be evaluated for competitiveness. Aggregating after the application of the competitiveness formula would constitute evaluating each trip’s competitiveness individually, and then creating a rule for using these individual evaluations to determine whether or not a row in the final dataset passes or fails. For example, a row could be deemed competitive if more than 50% of the trips within that aggregation are determined to be competitive.

At MassDOT/MBTA, we are going to compare the results of using aggregate-level routing as well as the results of the two processes to assess the magnitude of the impact and under which contexts the different processes create different results, as discussed in detail earlier.

3.2.4. How many meaningfully different “competitiveness formulas” are there and what are these formulas?

In this step, the decisions will focus on what level of a factor crosses a “threshold” pertinent to the evaluated competitiveness of transit. For factors pertinent to network quality for which there is no analogous inconvenience associated with driving (e.g. walk distance, frequency, and number of transfers), a certain level of imperfection is baked into transit riders’ decision to use transit. For each factor, there is a level at which transit is determined to be comparable to driving (fully competitive). On the other hand, transit itineraries may technically exist, but may be of such poor quality that most riders do not functionally think of it as an option (e.g. if the transit itinerary requires three transfers). This means that there is also a level at which transit is determined to be a reasonable, if not fully competitive, option in comparison to driving (sufficiently competitive). For example, a 10 minute frequency is usually treated as the maximum for service to be considered fully competitive, and a 20 minute frequency as the maximum for service to be considered sufficiently competitive, and thus tolerable (National Academies of Sciences, Engineering, and Medicine, 2013).

For factors with a driving analog (e.g. travel time, reliability), the relevant question is at what ratio is transit competitive with driving? For example, with travel time, past research indicates that transit can take up to 1.25× as long as driving and be comparable to driving, and can take up to 1.5× to 2× as long as driving and still be sufficiently competitive (National Academies of Sciences, Engineering, and Medicine, 2013; Arellano Associates, 2019).

In the end, competitiveness formulas will constitute a list of conditions that the transit routing must pass. The following example formulas are meant to be representative of the functional form, rather than of the specific thresholds that ought to be used.

Example formulas:

- Transit is **comparable to driving** for the median rider if
  - o First/last mile connections are at most 0.25 miles
  - o Services used are scheduled to come at least every 10 minutes
  - o At most 1 transfer is required
  - o The transit trip takes at most 1.25× as long as driving
- Transit is **sufficiently competitive** for the median rider if
  - o First/last mile connections are at most 0.75 miles
  - o Services used are scheduled to come at least every 20 minutes
  - o At most 2 transfers are required
  - o The transit trip takes at most 2× as long as driving

At MassDOT/MBTA, we are using public input to determine what thresholds are most appropriate for our system. The routing parameters in an earlier stage are captured in values rather than in passing/failing of thresholds in order to allow for evaluation of different thresholds based on public input. We are aiming to provide our outreach efforts with a calculation based on thresholds from prior outreach, surveys, and research, and then based on feedback, tweak the thresholds to better reflect perception of high-quality transit.

The process of conducting this outreach, especially with populations that we suspect may have different needs, will also generate the data necessary to determine how many meaningfully different contexts exist with meaningfully different competitiveness formulas.

Different contexts are defined by characteristics associated with either individuals or trips that need meaningfully different levels of service for one of the factors being included in a competitiveness formula. For example, a competitiveness formula for seniors and people with disabilities may necessitate a lower maximum acceptable walk distance than the general population. Alternatively, some individuals may not mind walking a relatively long distance to high-quality transit for commute trips, but minimizing walk distance becomes important to them for grocery trips or other errands where they have to carry a substantial load.

This framework will produce substantially fewer "competitiveness formulas" than suggested by most of the mode-choice literature because much of the complexity involved in modeling an individual's perception of transit quality does not have to be captured. First, a characteristic would only necessitate a different context if the strength of the effect were large enough to necessitate a different network design. There is extensive research into statistically significant differences between groups, but these differences are small enough that the added complexity produces too much of a barrier to implementation without producing proportional benefit. Second, contexts are defined by how an individual would assess transit as an option in comparison to driving, rather than how an individual would assess transit as an option in compassion to an alternative transit option. This does not account for individual preferences within trade-off exercises if individuals view neither or both options as competitive. For instance, some individuals may prefer walking further to higher frequency transit, while others may prefer less frequent transit closer to their home, but this preference does not indicate the need for different formulas if both groups still view either transit option as being competitive.

The key decision for the measure is to determine how many formulas there are in the region that are different enough that they should be calculated independently. Each different context will result in a separate calculation of the measure, with the ability to make statements like, "The current network serves work-related trips well, with X% of trips having a competitive transit option under that formula. However, the network is less well-suited for travelers with disabilities, with only Y% of trips having a competitive transit option under this formula."

For MassDOT/MBTA, because we are only interested in a limited number of factors, an origin-destination-time period combination is determined to be competitive only if it meets the thresholds set for *all* factors under consideration. If a much larger number of factors is under consideration, a smaller number of critical factors could be identified for each context that would be treated as necessary conditions to determine that a row within the travel demand dataset is competitive.

3.2.5. How will trips by populations of interest be identified?

By identifying the populations of interest, we can identify the measure for trips made by those populations, allowing a direct comparison between the general network quality and the network quality for populations of interest. Depending on the source data for travel, this identification can have many forms; at MassDOT/MBTA, because we're using location-based services data, we are using the device's home address to assign it as likely belonging to a low-income person or person of color, as described in Section 3.1.2. The equity check will need to be conducted for every competitiveness context identified in a previous stage.

3.3. Regional access measure implementation guide

Measure: the proportion of residents (in environmental justice communities) that can reach their local and regional destinations with a competitive transit option under each transit network alternative.

This measure is focused on supporting the regional economy and local living; it assumes that current travel is a good way to identify the places where people want to go when they travel, but doesn't necessarily capture all trip-making that people want to do. Therefore, it uses the travel dataset to identify high-demand destinations that need to have competitive transit access, and assumes that all residents should have competitive transit access to the regional destinations, and to their specific local destinations.

3.3.1. What is the unit of measurement?

The limiting factor for the units of measurement used for identifying destinations will be the level of aggregation for whichever dataset will be used to evaluate what counts as a destination (see next stage). Due to how our data is structured at MassDOT/MBTA, we will evaluate our custom Bus Analysis Zones (BAZs) as the base unit of measurement for regional and local destinations. The rest of this guide pre-supposes this level of aggregation, but it can certainly be more precise (e.g. individual institutions), if this data is available.

3.3.2. What counts as the universe of destinations (the denominator in the proportion)?

For regional destinations, we identify centers that generate so much travel as a destination that they need to have competitive transit access from anywhere in the region. How this set of destinations is constructed will vary depending on the dataset and region. At MassDOT/MBTA, we are using the travel dataset to identify the top destinations, focusing on volume, trip lengths, and dispersion. This list could easily be generated by other means (e.g. public input, using other information like density of employment, etc.).

For identifying regional destinations, MassDOT/MBTA created origin-based rankings of destinations using an index of trip volumes, lengths, and dispersion. We evaluated these rankings for each population of interest to determine the regional destinations important to all populations.

In the Boston area, regional destinations include locations with the highest trip-making volumes in the region, often including both high levels of commute and non-commute demand: places like the Longwood Medical Area, the Financial District, and Back Bay.

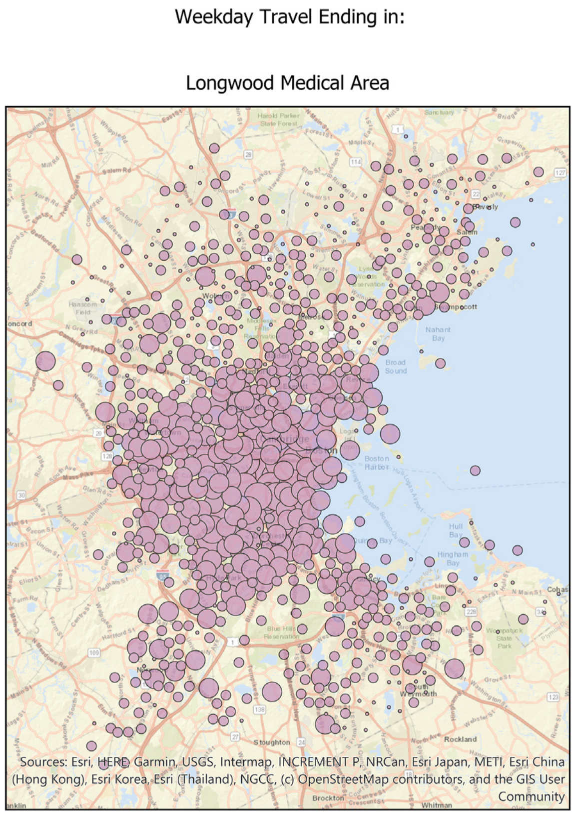

Fig. 1. Example of trip-making from a regional destination in the MBTA service area.

Fig. 2. Example of trip-making from a local destination in the MBTA service area.

Fig. 1 below depicts trip-making from the Longwood Medical Area.

Local destinations are locations that generate travel but perhaps at lower volumes and with less dispersed origins than the regional destinations. These local destinations could be single institutions with a significant demand (e.g., universities or hospitals) or they could be neighborhood commercial districts and town centers that draw many people from nearby towns. Fig. 2 below depicts trip-making to Roslindale Village, the main streets area of a Boston neighborhood. The volume is still generally high, but not as high as in a regional destination, and attracts travel from a smaller subset of communities compared to Longwood Medical Area.

Again, how the list is generated can vary. At MassDOT/MBTA, we're using a similar process as for regional destinations. For each zone, we removed the regional destinations from the dataset, and used the next highest volumes of travel to determine the local destinations.

3.3.3. How big is one destination?

Frequently, especially for regional destinations, the area will span a fairly large geography. Decisions will need to be made around the maximum size for the destination (does it need to be walkable end to end? How many Block Groups can be said to be in the "Airport" destination, for example?). At MassDOT/MBTA we are using our Bus Analysis Zones (BAZs) as the size of a destination because these geographies were created specifically to represent an area that we could consider served should it contain any bus service. However, depending on the geographies (particularly if they are small) and the situation to which the regional access measure is being applied, researchers may want to create one single destination out of many geographic units of analysis.

3.3.4. Which destinations are in a resident's universe?

Each BAZ serves as an origin for some number of trips; local destinations could be determined to be a subset of destinations from each BAZ, likely set at some proportion of travel originating in the BAZ or at some number of destinations. At MassDOT/MBTA, we developed a public engagement tool that allows members of the public to input an origin address, displays the travel patterns from that origin's BAZ, and allows the user to report the travel cut-off that most represents what they think of as their local travel shed. We will use the results collected from public feedback to determine the appropriate cut-off for determining location destinations for our region. The end threshold will likely be in the form of, "For each origin BAZ, local destinations are identified as the top X destinations from the origin" or "For each origin BAZ, local destinations are based on covering up to X% of travel".

3.3.5. What will be the routing data construction process?

The routing universe will likely depend on the units of measurement determined in an earlier stage. For our evaluation, we will be using BAZs for both residential and destination locations; this data is going to already exist from the routing conducted for the mode shift measure, and will just require scaling that data to residents rather than to number of trips.

3.3.6. How will regional access be calculated for equity populations?

Because the regional access measure is residence-based, access for EJ communities can readily be compared to overall regional access. The measure can be calculated for the residents of EJ communities only and compared to the measure calculated for the region as a whole. In fact, any community can be evaluated on its own to create a measure of relative access for that community compared to the region or any other community. So, depending on populations or communities of interest, it is possible to use this measure to evaluate for regional inequities in provision of access.

4. Discussion

This paper provides transit agencies with a comprehensive framework for evaluating their transit network and helps them produce two measures that can be used in the policymaking process to determine the quality of the current network and compare it against possible network alternatives. This section focuses on the feasibility of applying this framework, and highlights some of its limitations.

4.1. Travel data feasibility

One of the key building blocks of this framework is a high-quality origin–destination dataset that describes overall mobility in the region of interest. While this type of dataset has been produced through travel surveys in the past, cell phone and location-based services (LBS) data provide new opportunities to acquire a more comprehensive dataset (National Academies of Sciences, Engineering, and Medicine, 2018). Moreover, because phone and location-based services data is constantly being collected, it is easier to acquire data for multiple years, as opposed to travel surveys, which would require a new survey effort every time new data would be needed to check on network performance. Travel survey data collection can be expensive and time-intensive. LBS data is also expensive, and typically requires a portion of data-processing to be contracted out due to the specialized expertise needed.

4.2. Region-specific measures

One of the key merits of this framework is its ability to evaluate the entire transit network at once. By using the trip as the unit of analysis and measuring performance relative to other transportation modes, we are able to disentangle the effects of land use, particularly density, from transportation-specific effects. This differs from cumulative opportunity measures, which tend to overestimate network performance in denser, smaller geographies relative to actual network quality. Additionally, this framework gives transit agencies the opportunity to calibrate its parameters to match the needs of their local riders. This again helps ensure that the measure reflects the realities of a particular region.

Having this level of flexibility built into the framework makes the measures a better representation of the everyday experience of riders, but it has its downsides as well. Since each region makes its own choices, it will not be possible to compare them to each other unless the same factors, weights, and thresholds are applied. Peer transit agencies could work together to utilize the same criteria or share origin-destination data to encourage comparisons. Further development is needed to create a more generalizable framework that can be used nationwide.

4.3. All trip purposes

Unlike more traditional network access measures, the measures in this framework do not curtail the scope of analysis to one specific trip purpose. Instead, the framework captures all trips done in the network and weighs them equally. This prioritizes overall travel demand in network design, instead of prioritizing more specialized networks that only work well for certain types of trips. Additionally, if agencies are interested in creating a more targeted network, they can select out trips for analysis that fall under a specific trip purpose, with the caveat that most cell phone data will not have this information. If using cell phone data, this issue may be mitigated by using time-series data to identify regular trips, which can be assumed to be a person's 'commute' (although this method does not capture less regular commuting patterns).

In practice, at least in the Boston region, the "priority places" and other destinations identified in various planning efforts, while focused on their economic/employment opportunities, also generate many other kinds of travel. Therefore, the effect of explicitly including all travel in the measure will likely only be meaningfully seen in rewarding off-peak service frequency more than most commute-based access measures do.

4.4. A measure of transit competitiveness, not necessarily transit quality

Since both measures in this framework are relative to auto-based travel, changes to road conditions that impact car trips will inherently affect how competitive transit is represented in the measure. For example, if a specific origin-destination is served by an uncompetitive rail line, but congestion worsens over time so that auto travel time increases sharply, the measure will show that the transit option is performing "better" than before, even if its actual performance has not changed. As mentioned earlier, measuring network performance this way differs from the norm, and may also differ from riders' perception of what competitive transit is. At the same time, we posit that this way of measuring performance matches reality more closely, as riders will still choose the mode that performs the best for trips they need to make, even if all the possible mode alternatives do not perform up to their standards.

4.5. Demographic under-representation

One of the main drawbacks of using a location-based services dataset is that some groups may be underrepresented in the captured travel. Also, a lack of demographic data associated with the dataset requires additional assumptions to be made regarding the mobility of specific demographic groups. As mentioned earlier in this paper, one example of problematic underrepresentation is seniors. On the other hand, travel surveys often overrepresent regular trips and underrepresent non-commute trips and short travel. Agencies should weigh the pros and cons and make the decision that makes the most sense for them.

Additionally, agencies need to consider ways of capturing the different preferences of demographic groups that tend to be underrepresented not only in the phone data but also in the data used to expand the location-based services dataset into a specific geography. This is particularly true for Limited English Proficiency populations and people with limited mobility, for whom U.S. Census data is unreliable and thus cannot be easily tagged in an LBS dataset.

4.6. Competitive trips does not mean competitive tours

One limitation of using individual trips as the unit of analysis is that individuals usually make decisions about their trips on the basis of all of their travel until they return home (i.e. trips are very rarely one-way; they are usually at least round-trips, and may even be part of a longer trip-chain). The measurement framework designates a one-way trip as having a competitive transit option without knowing whether transit was a reasonable option for *all* of the trips within the tour. For example, an individual's commute to work may be deemed competitive, but they would be unlikely to view transit as a reasonable option if the service was not available during their return trip home.

4.7. Underlying assumption of transit user behavior

This framework assumes that individuals' stated preferences accurately reflect their decision-making process. That is, it measures competitiveness based on what users say is good service. However, if riders' stated preferences differ greatly from their actual decision-making process (e.g. if riders overstate how important a comfortable trip is when in reality they'll only take transit for trips that are faster than driving), this framework could overemphasize factors that individuals claim to value but that do not have a meaningful effect on mode-choice.

5. Conclusion and next steps

The Competitive Access framework provides a starting point for transit agencies and researchers who are interested in focusing on transit's competitiveness with auto-based modes at the network level, but how it will fit into the state of the operational and research fields is to be determined. While this framework provides agencies with the opportunity to measure network performance, it is not able to predict the magnitude of change in mode shift and ridership. Due to the limitations described above, the framework is meant to assist policy makers with assessments of existing and theoretical networks and provided service, not serve as an alternative to a ridership estimation model.

At MassDOT/MBTA, we expect to finalize the decisions and measures in this framework in the process of the Bus Network Redesign, and use it for evaluating proposed alternatives. We are simultaneously working on incorporating Competitive Access as one of the measures of the Service Delivery Policy (MBTA, 2017), and making sure it links up with the other network-level measures in that policy (most critically, the service availability/geographic coverage measure and cost-benefit ratio tool), which will also be used to evaluate network alternatives.

In addition to using the Competitive Access measures in the Bus Network Redesign, we expect to be able to quantify the impacts of Service Planning improvements (e.g. new bus/bike lanes, transit signal priority, and other improvements to transit quality) in the Competitive Access scores of the region.

On the research side, we expect to use the measurements of trip coverage and regional access as predictors of transit market share and, once we have longitudinal data, of mode shift. Among other predictors, we will need to include transit propensity (e.g. proportion of zero-vehicle households, density of land use), to determine whether these variables continue to significantly predict market share once competitive access is incorporated.

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Anna Gartsman: Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Project administration. **Alissa Zimmer:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Joaquin Osio-Norgaard:** Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Monisha Reginald:** Methodology, Writing - original draft, Writing - review & editing.

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